Chapter 2

Advanced Linear and Nonlinear Control Design

Rotor angle stability of a power system, as introduced in Chapter 1, concerns the electromechanical dynamics of generator rotors [2-1,2-2]. The rotors of all connected AC generators must operate at the same synchronous speed. Small oscillations between generator rotors occur frequently. Changes in the rotor angle relationship between generators are a function of generator loading, the distribution of loads in the network and the topology of the electrical network. The rotor angles between generators normally change very slowly as the system changes operating point through daily, weekly and seasonal cycles. Short-term transients will occur following a disturbance to the power system, and oscillations may arise from slowly evolving operating conditions.

As is the case with essentially all physical phenomena, power system rotor angle stability is inherently a nonlinear control problem. The control problem in power system angle stability has several additional complicating factors. These include:

- An accurate mathematical representation of an interconnected power system is usually of very high order, often containing several thousand state variables;
- The system is multivariable, often containing numerous generators each with their own controllers;
- The system is continuously time varying, with daily and seasonal cycles as well sudden short term changes;
- The system often contains significant levels of noise due partly to the constant changing of many loads;
- The system contains numerous nonlinearities, including saturation of generators, exciters, nonlinear power transfer characteristics and nonlinear load characteristics;
- An interconnected power system covers a large geographic area, which may make communication and monitoring of the system difficult and expensive.

Despite all of these difficulties, many aspects of the control problem are addressable in terms of the vast amount of theoretical information applicable to linear, or linearizable, systems.

When a disturbance impacts a generator's mechanical and electrical torque balance, the rotor of that machine must either speed up or slow down. The electrical torque will often change more rapidly than the mechanical torque input because it is dependent upon the electrical network variables which can change rapidly. These variables include the power transmission capacity of the network and the state of all other machine rotors in the system. The changes in electrical torque within a generator can be resolved into two components, one in phase with rotor angle and the other in phase with rotor speed. These components are often referred to respectively as synchronizing and damping torques [2-3]. These concepts can be generalized in terms of state space modeling [2-68]. These concepts illustrate two separate aspects of the rotor angle stability problem. A lack of synchronizing torque often leads to rotor angle instability in the first swing of the generator rotor. Synchronizing torque is restored by fast acting control actions. The problem is referred to as the transient stability problem. The control actions include fault clearing, network reconfigurations, generator fast valving [2-4], resistive breaking, or generator tripping [2-5–7] and they often do not utilize feedback. Some recent works however have incorporated feedback control for fast valving [2-8].

In contrast, control designs to enhance damping torque usually rely on applications of theory from linear feedback control design, and occasionally nonlinear feedback control design. These control designs deal primarily with small disturbance stability described in terms of linear control concepts such as eigenvalues, poles and zeros, bode plots, and damping. Some common control actuators for small signal stability are generator excitation systems including power system stabilizers (PSS), power electronic devices, modulated loads, and HVDC links. Reference 2-53 provides an overview of rotor angle stability related to PSS. Some recent works have discussed the plausibility of using feedback control to modulate the system loads to improve damping [2-9,2-10]. In any disturbance both the synchronizing torque and damping torque aspects of the rotor angle stability problem exist. Small-disturbance stability (damping torques) must always exist, and large-disturbance stability (synchronizing torques) should exist for most severe disturbances.

Knowledge of the stability conditions of an interconnected power system is vital for reliable operation. The availability and proper design of stability controls can significantly extend the safe operating limits of interconnected power systems.

2.1 Nonlinear Control

Although power systems are inherently nonlinear most of the control design used in practice is based on linear control theory. In recent years, however, there have been several advances in the application of nonlinear control theory. The main impetus is to obtain more effective controllers by having the design account for the system nonlinearities. References 2-11 and 2-67 discuss aspects of the nonlinear nature of power systems.

Feedback linearization. One approach involves feedback linearization. The nonlinear dynamics of the system are transformed into a linear (or partially linear) system so that linear control techniques can be used. References 2-12 and 2-42 discuss theoretical aspects. The result is a transformation or an input signal that contains a nonlinear as well as a linear component. This approach has been applied to power systems to control generator power [2-8,2-13]. Both papers illustrate a significant improvement in damping and transient stability of the power system when the mechanical power input to the generator can be effectively controlled. Reference 2-54 presents the application of feedback linearization to excitation control for angle stability of a multi-machine system. Reference 2-66 describes feedback linearization applied to a small parallel AC/DC test system for the enhancement of transient stability.

Adaptive control. Some or all of the nonlinearities are treated in terms of time varying changes in the system. As the system changes its operating point, a model of the system can be determined and the control applied according to information about the model or the deviation of the system from the model. There are many approaches to adaptive control. Some conventional adaptive controllers have been applied to power system problems [2-14–16]. There are also adaptive control approaches involving fuzzy systems and or neural nets [2-17–19].

Cost function. This approach to nonlinear control design involves the use of a cost function or penalty function to evaluate the effectiveness of controller parameters for a given control structure. In reference 2-20, a simple quadratic cost function is used to evaluate controller design parameters for a TCSC. The method involves a large number of simulation studies to determine the best set of design parameters for a set of operating conditions and expected disturbances. This approach is only feasible when the number of design parameters to be determined is relatively small.

Discontinuous control. Discontinuous controls or “bang-bang” controls are the most commonly used emergency measures for maintaining transient stability when large disturbances occur in a power network. Examples include generator tripping, series capacitor switching, generator excitation boosting, and dynamic braking. These approaches are very effective in mitigating disturbances and maintaining rotor angle stability during the first swing of the rotor angles. The basic problem in most of these strategies is to determine the appropriate level of control action and the correct timing for the switching actions. In general this is a nonlinear control problem. In some cases the problem may reduce to being able to detect the appropriate conditions and begin the control sequence. Many of these approaches rely on detailed and extensive simulation studies and they do not utilize feedback. References 2-6, 2-21–23, and 2-80 describe these types of control. Some approaches do utilize feedback [2-24].

Normal forms. Recent work on nonlinear control using normal forms indicates that stressed power systems exhibit characteristics that can be addressed by including additional terms in the Taylor series expansion of the nonlinear system. References 2-25 and 2-26 discuss the basic theory behind normal forms. The standard approach for linearizing a nonlinear system involves using only the first or linear term in the Taylor series expansion of the nonlinear system. All higher order terms are neglected in linear analysis. Normal forms include the effects of some higher order terms in the Taylor series expansion and can provide insight into the modal interactions exhibited by power systems. Both the linear approach and the normal forms approach use approximations to the full nonlinear system, but the normal forms approach is able to include more of the system nonlinearities. Reference 2-27 is concerned with including second order terms to affect nonlinear tuning of controller gains.

Dissipativity. Reference 2-52 proposes a unifying framework for analysis and synthesis of controllers to damp low frequency oscillation in power systems. The basic idea is that a passive system always consumes energy. The controllers can be HVDC links, static var compensators (SVCs), thyristor controlled series capacitors (TCSCs) and power system stabilizers.

Energy (Lyapunov) function methods. The application of energy (Lyapunov) function methods in transient stability analysis of electric power systems is well known [2-71,2-

72]. In recent years, use of energy function principles to derive control strategies for large-scale power systems has received increased research attention [2-73,2-74,2-75]. Advantages of energy function control strategies are that the form is independent of the structure, i.e., structural uncertainty is not a main issue; they may rely on local signals, and they have large regions of validity as they are based on the nonlinear system. A main limitation is that the derivation requires that an energy function of the system model be found. This results in modelling assumptions that are rather restrictive. Grönquist et al. [2-75] study the effects of applying controls to FACTS devices based on energy function methods for lossless system models.

Reference 2-74 investigates and evaluates transient stability enhancement of large-scale power systems by control strategies for unified power flow controller, controlled series compensation, and phase shifting transformers. The controls are applied to a CIGRÉ test system that has dynamic properties similar to the Swedish and interconnected Nordic power system. Reference 2-73 describes control strategy for HVDC converter controls based on energy function methods.

Nonlinear fuzzy and neural net control. As described in Chapter 4, fuzzy system and neural network applications to rotor angle stability problems is a research area. The advantage of fuzzy controllers is their ability to incorporate nonlinear effects into the resulting control surfaces. An important problem to overcome in power system angle stability applications is that an expert may not be available to provide guidance in forming the fuzzy rules due to the complexity and variability of the dynamic processes. Reference 2-70 describes an integrated fuzzy controller for voltage regulation, power system stabilizer and governor control of a generator. Field tests of a fuzzy PSS are also briefly described. Neural nets provide another and perhaps complimentary solution to the nonlinear control problem through their capacity to learn from system conditions and model nonlinear effects. References 2-28 and 2-29 recent work in this area.

2.2 Linear Control Techniques

Power system linear control design is a process that can be divided into distinct steps; the number depends on the situation. One situation arises if the control principle is already decided. Reference 2-30 proposes a three-step design procedure for end-use load control. The steps are: 1) select a location for control actuation, 2) choose feedback signals, and 3) select the compensating parameters.

Another design situation occurs if the control principle is not yet decided. Then the problem is to find the most cost-efficient way to solve the angle stability problem. The key question is to find and evaluate different alternatives. These can range from engineering work retuning existing controllers such as PSS, to large investments in new power electronic devices. Some alternatives are listed below:

- Retune existing PSS, AVR, and HVDC link and SVC controllers.
- Upgrade control equipment for existing primary controllers such as HVDC, SVCs.
- Add control equipment to existing devices. For example, load modulation control of electrical heaters used in district heating.

- Add a new power electronic device.
- Strengthen the primary system with a new transmission line.
- Calculate system operating restrictions on-line.

Eigenvalue sensitivity [2-31] and participation factors [2-2] are well-known methods of locating control equipment; see also references 2-32, 2-33 and 2-62. Structural aspects of controlling active loads are presented in reference 2-32. Reference 2-63 describes a controller design and analysis approach to adjust the existing structure of a system by retuning the internal control loops to relocate critical zeros, thus removing the constraints that arise when zeros are at unsuitable locations. Retuning is based on an existing extension of modal analysis to linear system zeros.

References 2-34, 2-55, and 2-36 discuss the use of transfer function residue information for placing and designing controllers. The residue of a transfer function is similar to the participation factor of a state space model. Residues provide information about which modes are most sensitive to gain variations, and what directions the poles will move when the gain is increased.

Modeling and model reduction. Design methods and model reduction are intimately related and some remarks are appropriate. Many advanced methods, especially for robust control, require extensive computations. Therefore it is not feasible to use design models as detailed as those used for time domain simulation. Either we adopt a reduced order model suitable for the design method, or we are restricted to design methods with moderate computation requirements. In automatic control, it is argued that the best model is the simplest one that is accurate enough to fulfill the design requirement. It's important to find a reasonable compromise between model complexity and the design method's computational requirements.

Reference 2-35 describes modeling and model reduction from a control perspective. It's pointed out that model reduction may involve:

a) model order reduction in a linear system;

b) model approximation of a nonlinear differential equations by linear systems;

c) approximation of the nonlinear system by ignoring higher-order harmonics.

Note that the case of model order reduction for high order nonlinear differential equations to low order nonlinear differential equations is not considered. This is actually the situation power engineers face when having a complex multi-machine simulation model that includes saturation nonlinearities and also nonlinearities in the power flow equations. For case a), MATLAB's Control System Toolbox offers usable tools for model reduction. References 2-36 and 2-37 present time-scale decomposition applied to power systems. This method is especially suitable for a design aiming at a certain frequency window, such as PSS design. Reference 2-38 outlines how synchrony, a generalization of slow-coherency, can be used to construct dynamic equivalents by aggregation of generators. The method is reported to be effective in decomposing the eigenanalysis of electromechanical modes

Identification of models. Another approach to obtain dynamic models for linear controller design in power systems is to use identification techniques on system input/output data. In reference 2-55 Prony analysis, modified for transfer function identification, is presented and in reference 2-56 this method is extended for robustness considerations. One advantage of this approach is that it can be applied to field data and does not strictly rely on simulation studies. The models obtained using these methods are generally reduced order because only the system modes observable in the output signal can be incorporated. Once the transfer function model is obtained any standard linear control design procedure can be used. One must be aware, however, of the limited range of validity of these models [2-56]. Additional recent work in this area is reported [2-57,2-58,2-61]. An extension of Prony analysis for multiple output signals is discussed in references 2-78 and 2-79.

Robustness. The need for robustness design depends on system properties. What are the possible operating conditions? Where are the load centers? Where are the generation areas? Are the power flow directions always the same? For example in the Nordel system that connects the Scandinavian countries, there is a common market for trading electricity. The normal trading pattern gives a power flow from Norway, through the Swedish west coast to Denmark. However, for years with little rain the power flow direction can be reversed. Here there is an obvious need for a robust design method that can handle two very different operating conditions. For other systems, such as the New South Wales system in Australia dominated by coal fired plants and well-defined load centers, the need for robust design is less pronounced. Robustness can include many different types of uncertainties and some are listed below.

- Different load flow patterns.
- Varying load levels during the day, week, or year.
- Load characteristics, such as voltage and frequency dependence, that might vary with seasons and time of day. In Sweden, a lot of electric heating is used during winter, and in summer air conditioning can be used. Their voltage and frequency dependence is very different.
- Uncertainty in the topology (structure) of the power system—some plants, lines or transformers might be taken out for maintenance.
- The dynamic model of the power system always has some level of parameter uncertainty. Some of these parameters are related to design, such as generator time constants and inductance. Once determined, their change is negligible. Other parameters such as AVR, PSS, and turbine governor are tunable parameters that are easy to change. Even if these parameters have been identified, there is always a risk of subsequent modification without updating the model.
- Some parameters change slightly during operation. Line resistance is temperature dependent and Load-Tap-Changers (LTC) can change the nominal transformer ratio.

The control principle itself might be inherently robust, i.e., it works with a very limited knowledge about the power system. For example direct load switching to damp generator oscillations only needs two impedances and one switching level [2-32]. In contrast, the design in reference 2-39 is based on a linear multi-machine model of the entire power system. Many blackouts are caused by cascading disturbances that were not foreseen. Ultimately the power system should be robust to unforeseen disturbances. Power oscillations are often triggered by an initial disturbance that can give a range of possible input amplitudes or operating conditions to the system. The design should also be robust to variation in disturbance amplitude and operating conditions.

Linear design methods. The linear control design literature is extensive. Many design methods exist for linear and non-linear systems, and some methods include uncertainty. See references 2-40–43. References 2-2 and 2-44 present overviews of design method for power system applications. The methods can be categorized in different ways such as:

- Linear (linear output or state feedback) or nonlinear (on-off) control law.
- Linear or nonlinear design method. For example LQ-design can use a nonlinear criteria to design a linear state feedback.
- By the physical device the design is aiming for, that is, design for PSS, AVR, HVDC, SVC, or load switching.
- By a development scale ranging from academic control methods, to methods used to design controllers implemented in the power system. The evolution of a design method goes through the evolutionary steps: theory, small illustrative simulation study, larger simulation study, redesign, preliminary field test, redesign, and finally working application in a power system.

It always falls back to engineering judgment when deciding whether an advanced design method is really necessary, or if a simple control scheme would be sufficient. Measurements of time synchronized phasors opens new possibilities to feedback laws that can be inherently robust. The control design must be simple enough to be reliably applied to a physical system.

LQG methodology. Linear quadratic (LQ) control design is an attractive theoretical approach that has not found wide application in practice. Reference 2-39 presents a linear quadratic (LQ) based design method used to find a feedback structure and parameters for PSS/AVR. MATLAB software [2-45] is the main modelling and design tool. A linearized multi-machine model is used to design an optimal LQ-controller with full state feedback. In LQ design a trade-off is done between input energy and performance. It’s suggested that the best generator to damp a certain mode is the one where the optimal controller uses most of its input energy. Instead of using a full state feedback, the feedback is restricted to a sparse structure where most signals are local and only a few strategic global signals are used. This structure is retuned by parametric LQ, that is, numerical minimisation of the loss criteria used in LQ-design. The method’s strength is that the design is done using a multi-machine model, so all PSS and AVRs design is coordinated and simultaneous. The weak points are that the design is done at one operation point and the method does not consider robustness. Reference 2-59 provides another example using LQ design on a very large power system.

LQG/LTR methodology. Linear quadratic regulators discussed in the previous section have appealing robustness properties, including guaranteed gain margins of 6 dB or greater and phase margins of at least 60 degrees. However such controllers require knowledge of all the system states which usually is not possible or practical in power system applications. In these cases loop transfer recovery (LTR) can be used to estimate unavailable states and still retain the robustness properties of full state feedback with LQG. LQG/LTR is used to design stabilizing controllers for a SVC in references 2-56 and 2-65, and an HVDC link in reference 2-64. Application to power systems is proceeded by identification of an effective low order transfer function which is used as the design model.

Desensitized Control. In reference 2-47 a single-machine infinite bus model is used to design a robust regulator integrating AVR and PSS functions. In the design the controller is desensitized, i.e., made insensitive to parametric uncertainties. In this way robustness is included in the design. The design method was originally developed for the "Four-Loops-Regulator" structure used by Electricite de France (EdF), but reference 2-46 shows that the method can also be used for a standard AVR/PSS structure. The method is used to retune EdF's voltage regulators, and the new values will soon be used in operation.

Robust Control, μ-design, H_∞. Robust control is a well-established discipline with textbooks and MATLAB toolboxes [2-43,2-48]. Reference 2-49 proposes a framework for robust stability assessment of controls in multi-machine power systems. Structured Singular Value (SSV) is used to determine stability for varying operation conditions. In the companion paper [2-50], the method is used in a simulation study of a four-machine test system. The simulation results show excellent accuracy of robust stability assessment for a wide range of operating conditions. Reference 2-51 points out that robust controllers designed by μ-design can produce extremely fragile controllers in the sense that vanishing-small perturbations of the coefficients of the designed controller destabilize the closed-loop control system. Reference 2-60 is another study of H_∞ control design to power systems.

Design methods for active load controllers. Control of active load can be used to improve angle stability. Reference 2-30 describes control of end-user loads in the western USA to enhance stability. Reference 2-9 describes modulated controllable loads for power system stabilization. It's found that a decentralised two-loop load stabilizer, using local bus voltage and frequency, adds damping to all oscillation modes.

Reference 2-81 presents an on-off damping controller for a single machine system. It was used during a field test in southern Sweden to damp oscillations at a 0.9 MW hydro power generator. The controller used estimated machine frequency as input and controlled a 20 kW resistive load via thyristor switches. The results indicate that on-off control of active loads is effective in terms of added damping, and that it is simple to tune and implement.

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